

PLoS Neglected Tropical Diseases
Climate Teleconnections and Recent Patterns of Human and Animal Disease Outbreaks
--Manuscript Draft--

Manuscript Number:	PNTD-D-11-00034R2
Full Title:	Climate Teleconnections and Recent Patterns of Human and Animal Disease Outbreaks
Short Title:	Climate Variability and recent Disease Outbreaks
Article Type:	Research Article
Keywords:	Rift Valley Fever, Chikungunya, Climate Variability, ENSO, Indian Ocean, Teleconnections, Vegetation Index
Corresponding Author:	Assaf Anyamba, Ph.D NASA Goddard Space Flight Center Greenbelt, MD UNITED STATES
Corresponding Author Secondary Information:	
Corresponding Author's Institution:	NASA Goddard Space Flight Center
Corresponding Author's Secondary Institution:	
First Author:	Assaf Anyamba, Ph.D
First Author Secondary Information:	
All Authors:	Assaf Anyamba, Ph.D Kenneth J. Linthicum Jennifer L. Small Kathrine M. Collins Compton J. Tucker Edwin W. Pak Seth C. Britch James Ronald Eastman Jorge E. Pinzon Kevin L. Russell
All Authors Secondary Information:	
Abstract:	Recent clusters of outbreaks of mosquito-borne diseases (Rift Valley fever and chikungunya) in Africa and parts of the Indian Ocean islands illustrate how interannual climate variability influences the changing risk patterns of disease outbreaks. Extremes in rainfall (drought and flood) during the period 2004 - 2009 have privileged different disease vectors. Chikungunya outbreaks occurred during the severe drought from late 2004 to 2006 over coastal East Africa and the western Indian Ocean islands and in the later years India and Southeast Asia. The chikungunya pandemic was caused by a Central/East African genotype that appears to have been precipitated and then enhanced by global-scale and regional climate conditions in these regions. Outbreaks of Rift Valley fever occurred following excessive rainfall period from late 2006 to late 2007 in East Africa and Sudan, and then in 2008 - 2009 in Southern Africa. The shift in the outbreak patterns of Rift Valley fever from East Africa to Southern Africa followed a transition of the El Niño/Southern Oscillation (ENSO) phenomena from the warm El Niño phase (2006-2007) to the cold La Niña phase (2007-2009) and associated patterns of variability in the greater Indian Ocean basin that result in the displacement of the centres of above normal rainfall from Eastern to Southern Africa. Understanding

	the background patterns of climate variability both at global and regional scale and their impacts on ecological drivers of vector borne-diseases is critical in long-range planning of appropriate response and mitigation measures.
Suggested Reviewers:	<p>Paul E Epstein, Ph.D Harvard Medical School paul_epstein@hms.harvard.edu Epstein is a widely-published professor at the Harvard Medical School and Harvard School of Public Health. His interests are tropical diseases, public health and climate change.</p> <p>Anthony Barnston , Ph.D Columbia University tonyb@iri.columbia.edu Dr.Barnston is an expert long-term climate observations and analysis, real-time forecasting of climate variabilty, ENSO and applications of climate forest products in agriculture and health.</p> <p>Charles Bailey, Ph.D. National Center for Biodefense and Infectious Diseases cbailey2@gmu.edu Dr. Bailey's areas of interest are infectious diseases,ecology, arboviruses and biodefense.</p> <p>Michael Glantz, PhD. University of Colorado Boulder michael.glantz@colorado.edu Dr. Glanz is interested in how climate affects society and how society affects climate, especially in how the interaction between climate anomalies associated with ENSO and affects human activities.</p>
Opposed Reviewers:	

1 **Climate Teleconnections and Recent Patterns of Human
2 and Animal Disease Outbreaks**

3
4 **Assaf Anyamba^{a*}, Kenneth J. Linthicum^b, Jennifer L. Small^a, Kathrine M. Collins^a,**
5 **Compton J. Tucker^a, Edwin W. Pak^a, Seth C. Britch^b, James Ronald Eastman^c, Jorge E.**
6 **Pinzon^a, Kevin L. Russell^d**

7
8 ^aNASA Goddard Space Flight Center, Biospheric and Hydrological Sciences Laboratory,
9 Code 614, Greenbelt, MD 20771, USA, ^bUSDA-ARS Center for Medical, Agricultural, &
10 Veterinary Entomology, 1600 SW 23rd Dr, Gainesville, FL 32608, USA, ^cClark Labs, Clark
11 University, 950 Main Street, Worcester, MA 01610, USA, ^dArmed Forces Health
12 Surveillance Center, Division of GEIS Operations, 11800 Tech Rd, Silver Spring MD 20904,
13 USA.

14 * To whom correspondence should be addressed. E-mail: assaf.anyamba@nasa.gov

15
16
17

62 **AUTHOR SUMMARY**

63 Interannual climate variability associated with the *El Niño*/Southern Oscillation (ENSO)
64 phenomenon and regional climatic circulation mechanisms in the equatorial Indian Ocean
65 result in significant rainfall and ecological anomaly patterns that are major drivers of spatial
66 and temporal patterns of mosquito-borne disease outbreaks. Correlation and regression
67 analyses of long time series rainfall, vegetation index, and temperature data show that large
68 scale anomalies occur periodically that may influence mosquito vector populations and thus
69 spatial and temporal patterns of Rift Valley fever and chikungunya outbreaks. Rift Valley
70 fever outbreak events occurred after a period of ~3-4 months of persistent and above-normal
71 rainfall that enabled vector habitats to flourish. On the other hand, chikungunya outbreaks
72 occurred during periods of high temperatures and severe drought over East Africa and the
73 western Indian Ocean islands. This is consistent with highly populated environmental settings
74 where domestic and peri-domestic stored water containers were the likely mosquito sources.
75 However, in Southeast Asia, approximately 52% of chikungunya outbreaks occurred during
76 cooler-than-normal temperatures and were significantly negatively correlated with drought.
77 Besides climate variability, other factors not accounted for such as vertebrate host immunity
78 may contribute to spatio-temporal patterns of outbreaks.

79

80

81 INTRODUCTION

82 Climate fluctuations leading to extreme temperatures, storm surges, flooding, and droughts
83 produce conditions that precipitate mosquito-borne disease epidemics directly affecting
84 global public health. Abnormally high temperatures affect populations of mosquito disease
85 vectors by influencing: mosquito survival; susceptibility of mosquitoes to viruses; mosquito
86 population growth rate, distribution, and seasonality; replication and extrinsic incubation
87 period of a virus in the mosquito; and virus transmission patterns and seasonality [1, 2].
88 Extreme increases in precipitation may increase mosquito larval habitats or create new
89 habitats and an overall increase in mosquito vector populations. For instance, the probability
90 of vector survival can increase with humidity [1-5]. Unusually low rainfall or drought can
91 also change habitats by concentrating water into small pools, potentially increasing the
92 proportion of container breeding mosquito vectors. Concurrently, these anomalous patterns of
93 temperature and precipitation have impacts on the vertebrate hosts of disease vector
94 mosquitoes. Increased rain can increase vegetation, habitat, food availability, and thus
95 survival of vertebrate host populations. Decreased rain can severely reduce or eliminate food
96 resources forcing vectors and vertebrate hosts into human settlements, increasing vector-
97 human contact [1-7].

98 The *El Niño*/Southern Oscillation (ENSO) phenomenon is a well known climate fluctuation
99 that is associated with extremes in the global climate regime. Over the last 30 years, a number
100 of studies have shown that climate variability associated with the ENSO phenomenon
101 influences several human and animal disease outbreaks including Rift Valley fever, Murray
102 Valley encephalitis, chikungunya, malaria, Hantavirus pulmonary syndrome, and various
103 other diseases [8-14]. ENSO is part of the earth's climate mechanism as inferred from various
104 reconstructions of millions of years of climate proxy data [15]. The influence of ENSO on the
105 global climate system, especially over the global tropics, through interannual variations in
106 temperature, atmospheric circulation, and precipitation at various distant locations is termed
107 *teleconnection*. Teleconnections produce differential anomaly patterns in these major climate
108 variables with the near-cyclical transitions through time from the warm *El Niño* phase to the
109 cold *La Niña* phase at the regional level around the world (Fig. 1). Teleconnections result
110 from the coupling between oceanic and atmospheric components of the earth's climate
111 system.

113

114 Periodic anomalous warming and cooling in the tropical central to eastern Pacific Ocean
115 region (ENSO) can trigger a tropospheric bridge effect that propagates globally. This
116 propagation is what triggers teleconnections and is postulated to have a lagged response of
117 between 3-5 months. The effect of these teleconnections is that they can trigger anomalous
118 convective activity, or lack of, at huge distances from the original site of warming [15-17].
119 These effects can be and are indeed modulated by coupled regional circulation patterns [18,
120 19]. The tendency for clusters of mosquito-borne diseases to occur simultaneously or a few
121 months apart during an ENSO cycle shows how extremes in rainfall resulting in either
122 persistent flood or severe drought can influence regional ecology and consequently dynamics
123 of mosquito vector populations at distant locations around the world, especially in the tropics
124 [10, 11, 13, 20].

125

126 At a gross global scale, the *El Niño* phase of ENSO causes distinct and simultaneous patterns
127 of flooding and drought (Fig. 1). Specifically, there is a tendency for wetter-than-normal
128 conditions and floods to occur over Eastern Africa, the southern tier of the United States,
129 Southern Brazil/northern Argentina and eastern-and-central Pacific Islands, Ecuador, and
130 Peru. Similarly, there is a tendency for drought to occur over a large area of Southeast Asia,

131 Australia, northern and north-eastern Brazil, and Southern Africa. These conditions are
 132 largely reversible during the *La Niña* phase of ENSO [16, 20, 21]. Such extremes in regional
 133 climate regimes can create ecological conditions that influence the emergence or re-
 134 emergence of mosquito vectors, their distribution and abundance (as well as those of their
 135 vertebrate hosts), their population dynamics, and the transmission of mosquito-borne diseases
 136 of global public health relevance [1,22]. Climate-disease teleconnection studies have been
 137 carried out, but most have been limited by poor reporting and a lack of geo-referenced
 138 disease databases. In this study we analyze and illustrate how recent outbreaks of two
 139 mosquito-borne diseases, chikungunya and Rift Valley fever [8,9,22-24], over Africa and the
 140 western Indian Ocean basin islands were coupled to specific climate anomaly patterns. We
 141 use geo-referenced disease occurrence data (Fig. 2), and explore spatial and temporal
 142 associations of disease outbreaks that change with variability in underlying climate and
 143 ecological patterns.

144
145

146 MATERIALS AND METHODS

147 To determine the ecological and climatic conditions leading to and associated with Rift
 148 Valley fever and chikungunya mosquito-borne disease outbreaks, we analyzed relationships
 149 between locations of outbreaks and patterns of change in vegetation, rainfall, and
 150 temperature.

151

152 Data

153

154 Rift Valley fever and chikungunya disease data

155 The baseline disease case location data used in this study were based on human and livestock
 156 epidemiological surveys by different institutions in various countries. These data are limited
 157 to outbreaks between 2006-2009 for Rift Valley fever in East Africa, Sudan, and Southern
 158 Africa. For chikungunya data, we compiled data from two sources. The first source was data
 159 from the recent epidemic in Eastern Africa and Western Indian Ocean islands, covering 2004-
 160 2006. The second source was a historical 1952-2010 dataset compiled from various sources,
 161 including literature in the online archives of the U S Centers for Disease Control and
 162 Prevention (CDC), the WHO, and other relevant sources to create a statistically robust
 163 sample for this study. We were primarily concerned with geographic locations of the disease
 164 cases in order to compare them with environmental data. At each historical outbreak location
 165 an approximate geographic latitude/longitude location was determined using place names.
 166 Historical outbreaks were located in East Africa, Central Africa, South Asia (primarily India
 167 and Bangladesh), and Southeast Asia, providing a broader historical context in which to
 168 analyze chikungunya-climate relationships. Most comprehensive geo-referenced records of
 169 chikungunya were limited to the recent epidemic period (2004-2010). Full details of
 170 chikungunya and Rift Valley fever case data are provided in section 3 and 5 of the Supporting
 171 Information and Material (SI).

172

173 Environmental and climate data

174 We utilized a number of environmental and climate data sets, described in detail in the SI.
 175 Satellite-derived Africa Rainfall Climatology (ARC) rainfall estimates for Africa and global
 176 surface air temperature and rainfall data from National Centers for Environmental Prediction
 177 and the National Centre for Atmospheric Research (NCEP/NCAR) were used to examine the
 178 climate anomaly patterns. The concept of teleconnections was illustrated using the Global
 179 Precipitation Climatology Project (GPCP) data set. SPOT Vegetation normalized difference
 180 vegetation index (NDVI) data were used as a proxy for ecological dynamics to assess and

181 infer ecological conditions associated with Rift Valley fever outbreaks. Table 1 summarizes
 182 the data sets used in this study.

183

184 **Approach**

185

186 We mapped disease location data on corresponding NDVI and climate data anomalies in
 187 order to understand associations between specific anomaly patterns in ecological and climate
 188 variables and disease outbreak patterns through space and time. We further explored the
 189 associations by plotting and comparing disease data against cumulative rainfall and
 190 vegetation index anomalies to illustrate the lag time between the driving climate conditions
 191 and the timing of first case disease occurrence for Rift Valley fever. For chikungunya we
 192 further investigated the relationships among surface air temperature, precipitation anomalies,
 193 and chikungunya outbreaks through correlation analysis. For Rift Valley fever we further
 194 investigated relationships between precipitation and Rift Valley fever outbreaks through
 195 logistic regression. Results were interpreted in terms of vector biology and population
 196 dynamics. We suggested caveats for non-outbreak years when climate and ecological
 197 conditions would indicate an imminent outbreak.

198

199 **Mapping and analysis**

200 **Anomaly calculations**

201 In general, for each climate/environmental variable, we calculated anomalies as follows:

202

$$203 X_a = X - X_u$$

204

205 where X_a = was the anomaly or difference of climate variable for any given month (X)
 206 from its long-term mean (X_u). The anomaly was a quantitative measure of the departure from
 207 normal/average conditions resulting in, for example using rainfall (Figs. 3 and 4), extreme
 208 wetness (above-normal rainfall, positive anomaly values) or extreme dryness (drought,
 209 negative anomaly values).

210

211 **Teleconnections mapping**

212 To illustrate the concept of teleconnections globally we calculated monthly rainfall anomalies
 213 for the GPCP data set based on 1979-2008 long term means. The rainfall anomalies were then
 214 correlated with the NINO3.4 sea surface temperature (SST) anomaly index by calculating
 215 Pearson's correlation coefficient over the monthly time series to produce the map shown in
 216 Fig. 1. Additional details of teleconnection analyses are provided in section 1 of the SI.

217

218 **Time-space mapping**

219 To illustrate the ecoclimatic teleconnection connection patterns in relation to Rift Valley
 220 fever outbreaks we plotted a Hovmöller diagram of NDVI anomalies for each outbreak
 221 region (East Africa, Sudan, and South Africa) against the NINO3.4 SST anomalies. This
 222 diagram showed the spatial and temporal dynamics of NDVI anomalies in relation to
 223 temporal dynamics of ENSO (represented by the NINO 3.4 index), Western equatorial Indian
 224 Ocean (WIO) SST anomalies, and the Rift Valley fever outbreak patterns. Details of how the
 225 Hovmöller diagram was derived are given in section 6 of the SI and the results are presented
 226 in Fig. 5.

227

228

Cumulative rainfall analysis

229 Since Rift Valley fever outbreaks are known to follow periods of extended above-normal
 230 rainfall, we calculated a cumulative rainfall anomaly index based on the ARC data set as
 231 follows:

$$232 \quad C_n = \sum_{i=1}^n R_i - \sum_{i=1}^n M_i$$

233

234 where C_n was the cumulative rainfall anomaly value for time steps 1 to n , \sum was the
 235 summation function, R_i was total rainfall at time step i of the series, and M_i was the average
 236 total rainfall for time step i . The time period was normally chosen to represent the rainy
 237 season, in which case C_n measured the difference between the current and average seasonal
 238 total rainfall [15]. To determine whether the ARC estimates indicated flood conditions, i.e.,
 239 where C_n was consistently positive, we calculated C_n for the months prior to reported Rift
 240 Valley fever outbreaks for four regions: East Africa (outbreak period December, 2006 to
 241 April, 2007), Sudan (September-November, 2007), Southern Africa (January-April, 2008),
 242 and Madagascar (March-May, 2008). A similar method was applied to NDVI data for
 243 outbreak periods for East Africa (2006-2007), Sudan (2007), and South Africa (2007-2008,
 244 2008-2009), and for the initial chikungunya outbreak period in East Africa (2004-2006). This
 245 index represents a proof of concept first suggested by Linthicum et al. [25], that Rift Valley
 246 fever activity follows widespread and above-normal rainfall enabling the emergence of large
 247 populations of Rift Valley fever vector mosquito species. Further details of cumulative
 248 rainfall analysis are provided in section 4 of the SI.

249

250 **Logistic regression**

251 In order to quantify the relationship between rainfall anomaly and the occurrence of Rift
 252 Valley fever, we used logistic regression. For each region (East Africa, Sudan, Southern
 253 Africa, Madagascar), we calculated the cumulative rainfall anomaly for the four months
 254 immediately prior to and including the onset of Rift Valley fever activity. These regional
 255 reference periods were as follows: (1) East Africa, September-December, 2006, for the
 256 December, 2006 outbreak; (2) Sudan, June-October, 2007, for the October, 2007 outbreak;
 257 (3) South Africa, October, 2007-January, 2008, for the January, 2008 outbreak; and (4)
 258 Madagascar, December, 2007-March, 2008, for the March, 2008 outbreak. For each outbreak
 259 site given in Fig. 1, we calculated the cumulative rainfall anomaly over the regional reference
 260 period for each year 2004-2008. The cumulative rainfall anomaly was expressed as a fraction
 261 of mean cumulative rainfall to make the regression coefficients independent of the rainfall
 262 unit of measurement. We coded Rift Valley fever presence with a 1 for the year of outbreak
 263 and absence with a 0 for all other years, and then ran a logit model regression of Rift Valley
 264 fever presence/absence on cumulative rainfall anomaly. The logit model was

$$265 \quad \pi_i = \frac{e^{(\beta_0 + x_i \beta_1)}}{1 + e^{(\beta_0 + x_i \beta_1)}},$$

266 where π_i was the code for disease absence/presence for observation i (1 or 0), x_i was
 267 the cumulative rainfall anomaly (expressed as a fraction of mean cumulative rainfall) for
 268 observation i , and the fitted coefficients, shown in Table 2, were β_0 (intercept term) and β_1
 269 (rainfall anomaly term).

270

271 **Correlation analysis**

272 For chikungunya, we tested the hypothesis that disease outbreaks were correlated with
 273 elevated temperature and/or drought by plotting occurrences against surface air temperature
 274 anomalies and precipitation anomalies under two scenarios. In the first scenario, meant to

275 simulate high temperatures and moderate drought, cumulative anomalies were made for a 3-
 276 month period prior to and then including the actual month of the case, for a total of 4 months.
 277 An example for April would be: January, February, March, and April anomalies aggregated
 278 to create the 4-month cumulative anomaly. Using the same method, a second scenario was
 279 constructed for a prolonged period of high temperatures and severe drought, except this time
 280 for a 7-month total. A frequency of occurrence was obtained by extracting values from each
 281 of the two scenarios for each of the chikungunya locations, for each region. For the
 282 temperature anomalies, the occurrences were classified as higher-than-normal if the
 283 anomalies were >0 , or cooler-than-normal if <0 . The precipitation anomalies were classified
 284 similarly as wetter-than-normal or drought if >0 or <0 , respectively. Because each geographic
 285 region had an occurrence sample size of ≥ 30 , the binomial test of significance was used. This
 286 test assumes a normal distribution, random sampling, and mutually exclusive data. A
 287 confidence level of 95% was assumed for the 2-tailed test. If the region's occurrences passed
 288 the test of significance, the nature of the relationship was tested by calculating the Pearson's
 289 correlation coefficient. Additional details of chikungunya correlation analyses are provided in
 290 sections 2 and 5 of the SI. Results by region are presented in Figs. 6 and 7.

291

292

293 RESULTS

294 Climate-disease teleconnections

295 The map in Fig. 1 shows the correlation between monthly NINO3.4 SST anomalies and
 296 monthly GPCP rainfall anomalies for 1979-2010. It illustrates how variations in sea surface
 297 temperature in the equatorial eastern Pacific (ENSO) influence rainfall variability at various
 298 locations around the world. It is also a depiction of the concept of teleconnections. The
 299 central to eastern Pacific Ocean region, Ecuador, Peru, Eastern equatorial Africa, and the
 300 southern tier of the United States indicate the tendency for wetter-than-normal conditions in
 301 these regions during the *El Niño* (warm) phase of ENSO. Negative correlations over Southern
 302 Africa and the western Pacific region, including Australia, the greater Indonesian Basin, and
 303 northern South America, indicate the tendency for drier-than-normal conditions during *El*
 304 *Niño* [10]. These anomaly patterns are largely reversed during the *La Niña* (cold) phase of
 305 ENSO as shown in previous studies [10]. Extremes in rainfall anomalies resulting from phase
 306 shifts in ENSO affect regional ecological patterns [11,12] differentially, and influence the
 307 emergence of different disease vectors and consequently patterns of vector-borne disease
 308 outbreaks [13,14]. In particular, there is a tendency for outbreaks of Rift Valley fever to occur
 309 in Eastern Africa during the *El Niño* phase and for outbreaks of Rift Valley fever to occur in
 310 Southern Africa during the *La Niña* phase, as will be shown later in this study.

311

312 Temporal sequence of outbreaks in relation to eco-climatic conditions

313 The 2004-2009 period of analysis is an illustration of the above teleconnection patterns and
 314 demonstrates how different climate and ecological anomaly extremes resulting from these
 315 teleconnections influence vector-borne disease outbreaks through variations in temperature,
 316 rainfall, and ecology. The clusters of outbreaks and epidemics/epizootics of chikungunya and
 317 Rift Valley fever across Africa (Fig. 2) [8,9,23,24] occurred during periods of severe drought
 318 for chikungunya (2004-2006; Fig. 3) [19,26], and during periods of above-normal rainfall for
 319 Rift Valley fever (late 2006 to 2009, Fig. 4) [8,27]. During 2004-2006 there was a regional
 320 chikungunya epidemic covering coastal East Africa that expanded to cover western Indian
 321 Ocean islands, and later parts of India and Southeast Asia through 2010 (Fig. S4). The bulk
 322 of the human cases were reported during the most severe drought period of 2005-2006 in East
 323 Africa and the western Indian Ocean islands. This chikungunya outbreak was consistent with
 324 drought resulting from circulation anomalies forced by the ENSO cold phase (*La Niña*) and a

325 regional circulation pattern characterized by anomalously high pressure in the western
326 equatorial Indian Ocean and low pressure in the east. These pressure patterns led to enhanced
327 surface westerlies, causing enhanced descending motion over East Africa and the western
328 Indian Ocean and ascending motion over Indonesia [21, 26, 27]. This pattern of regional
329 circulation hampered convective activity and precipitation and resulted in one of the most
330 severe droughts ever observed in the region (Fig. 2).

331

332 Historically, chikungunya is known to be enzootic in west and central Africa in a sylvatic
333 cycle involving wild non-human primates and forest species of *Aedes* mosquitoes [28]. The
334 first and subsequent documented outbreaks of chikungunya occurred during periods of heavy
335 rainfall, filling natural and artificial containers that serve as immature mosquito habitats [29,
336 30]. However, in 2004-2006 the severe drought described above [26] led to widespread
337 storage of water in containers around households. Unprotected stored water allowed *Aedes*
338 *aegypti* on the East African coast [9, 31] to reproduce in large numbers and permit
339 establishment of a Central/East African genotype of chikungunya virus in highly populated
340 areas of the East African coast and the western Indian Ocean islands [28]. In addition and
341 possibly most importantly, elevated temperatures during the drought facilitated the
342 amplification of the virus and increased vectorial capacity in the mosquitoes [9, 31].
343 Exposure of *Ae. aegypti* larvae to similarly elevated temperatures in the laboratory has been
344 shown to select for strains adapted to survive longer at these temperatures and significantly
345 increase susceptibility of adult mosquitoes to chikungunya virus, enhancing vectorial
346 capacity and vector competence, respectively [32]. This suggests *Ae. aegypti* was adaptable
347 to actual environmental conditions of severe drought and elevated temperatures presented
348 here. The initial chikungunya cases were identified at health care facilities in Lamu (June,
349 2004) in the initial stages of the drought, and Mombasa (November, 2004) as the drought
350 peaked in Kenya (Fig. 3).

351

352 In time the chikungunya outbreak spread and impacted the western Indian Ocean islands
353 including Seychelles, Comoros, Mayotte, Mauritius, and La Reunion, all in 2005, infecting
354 between 30-75 % of the populations in affected areas [2,21] (Figs. 2 and 3). The entire
355 western equatorial Indian Ocean region was impacted by a large scale drought in 2005 (Fig.
356 3) [26]. In December, 2005 a mutation was observed in some of the chikungunya isolates
357 from La Reunion that caused a single amino acid substitution in the E1 envelope glycoprotein
358 (E1-A226V) [33, 34]. Although *Aedes albopictus* was considered a competent but secondary
359 vector of chikungunya [35], the E1-A226V mutation increased virus replication and
360 dissemination in this mosquito, enhancing its vector competence and increasing the potential
361 for the virus to permanently extend its geographic range [33,34]. As many as 3 other
362 independent events led to the E1-A226V mutation in India, Cameroon, Gabon, and Sri
363 Lanka, and geographical expansion of the adaptation of the virus to *Ae. albopictus* [36, 37,
364 38]. Subsequently the outbreak continued eastward affecting many Indian Ocean countries
365 and in conjunction with human travel and tourism affected some European countries [9, 24,
366 33; SI].

367

368 Cessation of the drought in eastern Africa was marked by the development of contrasting
369 patterns of SST anomalies in the equatorial Indian Ocean, with positive SST anomalies in the
370 equatorial western sector and negative SST anomalies in the eastern sector, and a warm
371 ENSO event in the eastern Pacific Ocean. These patterns of SST anomalies (Fig. S1) and
372 associated precursor pressure anomalies led to enhanced easterlies, fast southern trade winds
373 and ascending motion over East Africa, and descending motions over Southeast Asia
374 [26,27,19]. The combined effect of these conditions resulted in persistent, above-normal, and

375 widespread rainfall in excess of 200 mm per month during September-December, 2006 in
 376 endemic regions of Eastern Africa (Fig. 4A) and severe drought conditions in Southeast Asia.
 377 The above-normal rainfall flooded low lying wetlands known as *dambos* [39], the primary
 378 habitats of *Aedes mcintoshi* mosquitoes pre-infected with Rift Valley fever virus from prior
 379 epizootics. The abnormally high and sustained precipitation led to not only rapid emergence
 380 and development of the mosquitoes, but also enhanced and sustained survival because of
 381 rapid emergence of protective vegetation habitat, as indicated by large positive NDVI
 382 anomalies (Fig. 4B) [10,23]. Large increases in numbers of virus-carrying mosquitoes in
 383 northeastern Kenya and southern Somalia quickly followed, and the first human Rift Valley
 384 fever cases were identified from serological surveys in mid-December, 2006 in Kenya and
 385 Somalia.

386
 387 The enhancement of *El Niño* and WIO positive SST conditions and then the shift in the main
 388 rainfall belt southwards into Tanzania resulted in a shift of the area at risk from Rift Valley
 389 fever activity southwards into Tanzania (Fig. 4A). The first cases of Rift Valley fever in
 390 humans were reported in Tanzania in February 2007 [23, 40]. While the Pacific NINO3.4
 391 region shifted to a cold phase with the emergence of *La Niña* conditions in May, 2007, the
 392 western equatorial Indian Ocean (Fig. S2) continued to warm with SST anomalies as high as
 393 +1°C between May-July, 2007. These conditions led to enhanced convective activity across
 394 the Sahel region with persistent and above-normal rainfall centred over central Sudan
 395 between June-October, 2007 (Fig. 4C). As in East Africa, these anomalous rains flooded
 396 *dambo* habitats and areas within the Gezira irrigation scheme as shown by the positive NDVI
 397 anomalies (Fig. 4D) resulting in the emergence of large numbers of Rift Valley fever-
 398 carrying *Aedes* and *Culex* mosquitoes. The first cases of Rift Valley fever in humans and
 399 livestock in Sudan were reported in mid-October, 2007. This was the first reported outbreak
 400 of Rift Valley fever in Sudan since 1976, although serologic evidence suggests an outbreak
 401 also occurred in 1981 [41,42].

402
 403 The shift from *El Niño* conditions to *La Niña* (Fig. S2) conditions in the summer and fall of
 404 2007 moved the main area of enhanced rainfall from Eastern to Southern Africa (Fig. 4E).
 405 The above-normal and widespread rainfall between October, 2006-February, 2007 resulted in
 406 flooding and anomalous green-up of vegetation in Rift Valley fever-endemic areas of
 407 Southern Africa (Fig. 4F) and Madagascar. Cases of Rift Valley fever in livestock and
 408 humans were identified in mid-February, 2008 and subsequently in some farm workers and
 409 veterinary students in South Africa. Human cases of Rift Valley fever were identified in
 410 Madagascar over a large part of the country from March-May, 2008 [23]. The persistence of
 411 *La Niña* conditions and enhanced westerlies in the equatorial Indian Ocean through mid-2009
 412 [20] resulted in recent and continuing severe drought conditions in East Africa and continued
 413 above-normal rainfall conditions in Southern Africa [43]. As a result there was a recurrence
 414 of Rift Valley fever activity in Southern Africa during the southern hemisphere summer
 415 period through 2011. Figure 5 summarizes the temporal and spatial anomaly patterns in
 416 vegetation (i.e., ecology) as they relate to the temporal patterns in SST anomalies and the
 417 resulting temporal distribution patterns of Rift Valley fever outbreaks for East Africa, Sudan,
 418 and Southern Africa during this period.

419

420 Comparison of chikungunya and Rift Valley fever with climate anomalies

421 An analysis of the January, 1979-February, 2010 relationships between chikungunya activity
 422 and surface air temperature anomalies and precipitation anomalies is shown in Figs. 6 and 7,
 423 respectively. The figures show the frequency distribution of the number of reported
 424 chikungunya outbreak events against rainfall and temperature anomalies. Persistent

425 temperature anomalies over a four month period were classified as hot if anomalies were >0
 426 or cool if <0 . Persistent precipitation anomalies over a 4 month period were classified as
 427 drought if <0 and wet if >0 . In East Africa, Central Africa, and South Asia, 94%, 68%, and
 428 80% of the outbreaks occurred during warmer-than-normal temperatures, and these
 429 differences were significant at $p < 0.05$ (Figs. 6A-C). However, in Southeast Asia 52% of the
 430 outbreaks occurred during cooler-than-normal temperatures (Fig. 6D). In East Africa
 431 outbreaks were also significantly positively correlated with drought conditions at $p < 0.05$
 432 (Fig. 7A), and not significantly correlated in South Asia (Fig. 7C). In Central Africa (Fig. 7B)
 433 and in Southeast Asia (Fig. 7D) outbreaks were significantly negatively correlated with
 434 drought at $p < 0.05$. The positive correlation between chikungunya outbreaks and warmer-
 435 than-normal temperatures in Africa and South Asia was consistent with non-sylvatic
 436 transmission by *Ae. aegypti* and *Ae. albopictus* in highly populated domestic settings where
 437 domestic and peri-domestic stored water supplies were the likely source of the mosquitoes [9,
 438 32, 33, 44, 45].

439
 440 The relationship between precipitation and Rift Valley fever was determined through a
 441 logistic regression of Rift Valley fever presence/absence on cumulative precipitation
 442 anomalies for the 4 months immediately preceding each Rift Valley fever outbreak [7,8] (Fig.
 443 S3 and SI). Results by region (East Africa, Sudan, South Africa, and Madagascar) are
 444 presented in Table 2. For all 4 regions a significant relationship was found between
 445 cumulative rainfall anomalies and Rift Valley fever presence with at least 99.9% confidence.
 446 For East Africa, Sudan, and South Africa this relationship was strongly positive ($\beta_1 > 0$), with
 447 the highest cumulative rainfall anomalies yielding the highest odds of Rift Valley fever
 448 presence, equivalent to an outbreak, as indicated by the positive rainfall anomaly terms
 449 estimated in Table 2. This relationship confirmed experimental findings by Linthicum et al.
 450 [S13] that persistent, widespread, and above-normal rainfall is required to flood *dambo*
 451 habitats in order to create ideal conditions to spawn abundant mosquito populations on a large
 452 scale that would result in a Rift Valley fever epizootic. As shown in Fig. S3, each of the
 453 selected outbreak locations for each region was preceded by above-normal rainfall for 3-4
 454 months before the first case of Rift Valley fever, which would likely create ideal ecological
 455 conditions for an increase in Rift Valley fever mosquito vector emergence and survival.
 456

457 In contrast, for Madagascar a negative relationship was found ($\beta_1 < 0$), with the model
 458 predicting higher odds of Rift Valley fever outbreaks when rainfall was less than normal.
 459 Although the 2008 Madagascar Rift Valley fever outbreak was initially triggered by rainfall
 460 [23, 46], the subsequent spread of the outbreak appears to have been related to the
 461 introduction of infected livestock. In Madagascar, livestock located in heavy rainfall areas in
 462 the south had become infected with Rift Valley fever and were then transported to other parts
 463 of the country to the north. Even though rainfall was only slightly above normal in these
 464 northern areas, precipitation was sufficient to produce abundant *Culex* populations
 465 originating from flooded domestic and semi-domestic immature mosquito breeding habitats.
 466 The *Culex* mosquitoes, efficient vectors of Rift Valley fever, then transferred the virus from
 467 the newly arrived infected livestock to surrounding human populations.
 468
 469

470 DISCUSSION

471 We have shown that inter-annual climate variability, as expressed by the ENSO phenomenon
 472 in association with regional climatic circulation mechanisms in the equatorial Indian Ocean,
 473 had broad influence on two mosquito-borne disease outbreaks over the greater Eastern Africa
 474 region, Southern Africa, and western Indian Ocean islands through opposite spatial shifts in

475 precipitation and vegetation anomaly patterns (Figs. 1, 4, and 5). In general, above-normal
 476 rainfall, cooler-than-normal temperatures, and above-normal vegetation development were
 477 strongly associated with the ecology of Rift Valley fever outbreaks, and drought and warmer-
 478 than-normal temperatures were associated with chikungunya epidemics in the greater East
 479 African region.

480 Historically, large scale outbreaks of chikungunya have been in large highly populated urban
 481 settings of tropical Asia, transmitted by *Ae. aegypti*, and in highly populated areas in Africa
 482 with smaller outbreaks limited to rural areas [30]. Current evidence as shown in this paper,
 483 however, illustrates that recent outbreaks in East Africa and western Indian Ocean islands
 484 occurred in coastal urban centres with large population densities [9,24,31] (Fig. S4).
 485 Additionally, the recent outbreaks in Gabon in 2010 have been in urban and suburban settings
 486 [47] and have occurred during a period of elevated temperature and drought as recently as
 487 May, 2010. This suggests that highly vector competent *Ae. aegypti* and *Ae. albopictus* exist in
 488 Africa and the greater Indian Ocean region [44]. Another property of historical chikungunya
 489 outbreaks was association with above-normal rainfall, such as the 1952-53 epidemic in
 490 Tanzania where excess rainfall in 1952 likely contributed to a spill over of the virus from a
 491 sylvan cycle involving *Aedes furcifer/taylori* and non-human primates to *Ae. aegypti* and
 492 humans. Yet, our findings here show that recent outbreaks, at least in East Africa and the
 493 western Indian Ocean islands, were favoured by extended and severe drought coupled with
 494 elevated temperature conditions [9,26,27] (Fig. 3). This suggests that *Ae. aegypti* has adapted
 495 well to urban settings in Africa, as it has in much of the tropics, sub-tropics, and temperate
 496 regions of the world, after its origin in sylvan Africa in the absence of human populations
 497 [45, 48, 49]. This also implies that *Ae. aegypti* has adapted to regional climate conditions in
 498 the western Indian Ocean region that were on average dry and rainfall-deficient compared to
 499 Southeast Asia [19].

500 In South Asia the occurrence of the majority of chikungunya cases during elevated
 501 temperatures during both rainy and drought periods strongly suggests that temperature alone
 502 was a major driving factor, involving both urban and rural transmission by *Ae. aegypti* and
 503 *Ae. albopictus*, respectively. On the other hand, the primary vector in Southeast Asia, *Ae.*
 504 *albopictus* is endemic and highly adapted to the prevailing wet climate regime that is its
 505 preferred habitat. As we have demonstrated here, this climate regime is primarily associated
 506 with rainfall and not elevated temperatures. This is consistent with rural transmission by *Ae.*
 507 *albopictus*, and may suggest the possibility of a sylvan cycle [50]. Although chikungunya,
 508 transmitted by *Ae. aegypti* largely disappeared from India and Southeast Asia in the late
 509 1970s-early 1980s [51, 52], both Asian and African genotypes are currently sympatric there
 510 [53]. The extent and scale of the 2004-2006 chikungunya epidemic in Eastern Africa was
 511 perhaps a revelation of Jupp and McIntosh's [31] hypothesis more than two decades ago that
 512 population growth in Africa with the associated urbanization would lead to epidemics on a
 513 scale similar to those experienced in Asia.

514 We have also illustrated that there was a spatial shift in the area at risk of Rift Valley fever
 515 activity from Eastern to Southern Africa in tandem with a phase shift from *El Niño* to *La*
Niña conditions in the eastern Pacific Ocean and SST anomalies in the western Indian Ocean
 516 (Fig. 5). Anomalously heavy, widespread, and prolonged rainfall events (Fig. 4) that caused
 517 Rift Valley fever outbreaks in domestic animals and humans in East Africa and Sudan (2006-
 518 2007) and Southern Africa (2008-2009) followed a transition of the ENSO phenomenon from
 519 the warm *El Niño* phase (2006-2007) to the cold *La Niña* phase (2007-2009), and the
 520 resultant displacement of the center of above-normal rainfall from Eastern to Southern

525 Africa. This elevated rainfall flooded mosquito habitats that introduced the virus into
526 domestic animal populations by producing large numbers of vertically infected *Ae. mcintoshi*
527 and other *Aedes* species mosquitoes. Sustained elevated rainfall then triggered production of
528 large populations of *Culex* mosquitoes that served as secondary vectors of Rift Valley fever
529 to animals and humans [10, 23]. As our findings here indicate, Rift Valley fever outbreaks
530 occurred during the short-rains seasons for East Africa (October-December), Sudan (October-
531 November), and Southern Africa (December-February). During some years, this period
532 occurred when there were enhanced equatorial easterlies that led to above-normal rainfall and
533 flood conditions over the eastern landmass of Africa [26, 27]. This pattern was particularly
534 enhanced when it was in phase with the warm episode of ENSO [Fig. 5; 8, 10, 21, 26].
535

536 Our analyses of the 2006-2009 Rift Valley fever outbreaks confirmed that there was a very
537 close correlation between outbreaks and persistent (i.e., 3-4 months) above-normal rainfall
538 [S13,S14]. The only known exception to this in sub-Saharan Africa was the man-made
539 flooding of mosquito habitats associated with the damming of the Senegal River in 1987 that
540 led to the large 1987-1988 outbreak in Senegal and Mauritania in the absence of excessive
541 rainfall [54]. In Egypt, outbreaks appear to be related to rainfall in the upper regions of the
542 Nile in Uganda, Ethiopia, and Sudan that results in flooding of habitats along the lower Nile
543 in Egypt. In Madagascar, rainfall precipitated the 2008 outbreak in the southern part of the
544 country, but the majority of human and animal cases actually occurred in other parts of the
545 country where ample *Culex* mosquito vectors in domestic settings efficiently transmitted the
546 virus to animals and humans. Still, there may be periods of heavy rainfall and ideal ecological
547 conditions that do not result in Rift Valley fever outbreaks (Fig. 5). This may be due to (1)
548 livestock and human population immunity, factors not fully understood, (2) changes in land
549 use, e.g., the transformation of *dambos* into agricultural land, (3) flooding events or the
550 timing, pattern, and distribution of rainfall that may not be consistent enough to support
551 sufficient batch hatching of multiple generations of vectors to result in an outbreak, and (4)
552 failure to detect disease outbreaks due to weak surveillance systems in sub-Saharan Africa,
553 particularly in the livestock/agricultural sector. In addition, only in the last 10 years have
554 georeferenced disease databases begun to be compiled, and often the data are spotty and
555 usually only gathered after an epidemic/epizootic has occurred. This type of outbreak
556 response reporting misses cases that occur in less severe climate and disease conditions and
557 thus largely go unreported.
558

559 CONCLUSION

560 Our knowledge of teleconnection events and the quasi-cyclical nature of climate variability
561 may allow parts of Africa, the Indian Ocean basin islands, and elsewhere within the greater
562 tropics to have more than a year warning prior to Rift Valley fever outbreaks [23] and other
563 humanitarian climate-related conditions, permitting more precise targeting of vaccine
564 strategies, mosquito control, animal quarantine, and public education strategies. Additionally,
565 identifying the potential for Rift Valley fever outbreaks to occur in Africa and controlling
566 these outbreaks will be of interest to regions of the world that are not currently endemic for
567 Rift Valley fever. The documented expansion of the range of Rift Valley fever beyond sub-
568 Saharan Africa into Egypt in 1977 [54] and into the Arabian Peninsula in 2000 [55,56,57]
569 makes Rift Valley fever a likely candidate for further expansion and a significant threat to
570 most of the world where immunologically naïve animal species and humans exist, and
571 competent *Culex* or *Aedes* vector mosquito species are present. Furthermore, there is a
572 significant economic threat from Rift Valley fever in non-endemic countries. For example,
573 the U.S. had beef related exports in 2003 of \$5.7 billion and should Rift Valley fever occur in
574 the U.S. the OIE will impose a 4 year trade ban until free of the disease for 6 months [58].

575 The climate-disease teleconnections examined here can also be used to better understand the
576 temporal dynamics of the burden of other diseases such as dengue, malaria, or cholera which
577 can be influenced by major climate events [11,12].

578

579 Outbreaks of mosquito-borne diseases on epidemic scales, such as those experienced during
580 2005-2009 in Africa and the western Indian Ocean islands, place a huge burden on public
581 healthcare systems and the economy. Outbreaks of chikungunya are also an impediment to
582 tourism, a major contributor to the gross national product of countries and island nation states
583 in the region. The costs to the economies of East Africa in lost trade in livestock due to Rift
584 Valley fever outbreaks were estimated to be \$65 million [59] during the 2006-2007 outbreak.
585 Furthermore, there is extended disruption in trade due to livestock movement bans following
586 an outbreak. Given the greater risk of spread and recurrence of outbreaks of these diseases, it
587 is critical that countries in the region have the capacity to anticipate the changing and variable
588 nature of the climate in the region to prevent or minimize the emergence and re-emergence of
589 such diseases. Therefore there is need for public health authorities to take advantage of
590 climate observations and analyses in times of extreme climate variability to aid response and
591 mitigation planning including vector surveillance and control, vaccination, and public
592 education in areas that may be impacted by disease outbreaks. In addition, climate-based
593 predictions offer opportunities for virologists, epidemiologists, entomologists, physicians,
594 and veterinarians to understand the biological and cyclic nature of the disease and how its
595 episodic occurrence relates to livestock immunity in recently infected areas, and the potential
596 for re-emergence of the disease in livestock and human populations.

597

598 It is apparent from our analyses that in changing and variable climate, arboviruses and their
599 mosquito vectors are going to adapt to the existing climatic and ecological conditions in a
600 new region, and the resultant disease transmission will vary accordingly and may not be the
601 same manifestation as observed in the original endemic regions. Combining satellite-derived
602 measurements and analyses of climate and ecology with an understanding of mosquito vector
603 biology and human and animal population immunity status can contribute substantially
604 towards reducing the global burden of vector-borne diseases.

605

606

607 **Acknowledgements.** We acknowledge the contributions of various personnel from the U.S. Army
608 Medical Research Unit – Kenya, U.S. Centers for Disease and Control – Kenya, Kenya Medical
609 Research Foundation, the World Health Organization’s Department of Epidemic and Pandemic Alert
610 and Response, the Food and Agricultural Organization of the United Nations, World Organization for
611 Animal Health (OIE), Ministries of Medical Services, Public Health in Kenya, Tanzania and Sudan,
612 Special Pathogens Unit, National Institute for Communicable Diseases and Ministry of Agriculture-
613 Livestock Department, Republic of South Africa, and the Institute Pasteur, Madagascar for collecting
614 and providing access to georeferenced human and livestock case data used in this study.

615

616

617

618

619

620

621

622

623 **References**

- 624 1. Gubler DJ, Reiter P, Ebi KL, Yap W, Nasci R, et al. (2001) Climate variability and
625 change in the United States: potential impacts on vector- and rodent-borne diseases.
626 Environ Health Perspect 109(S2): 223-233.
- 627 2. Epstein PR (2005) Climate change and human health. N Engl J Med 353: 1433-1436.
- 628 3. Turell MJ, O'Guinn M, Dohm DJ, Jones JW (2001) Vector competence of North
629 American mosquitoes (Diptera: Culicidae) for West Nile virus. J Med Entomol 38:
630 130-134.
- 631 4. Glass GE, Cheek JE, Patz JA, Shields TM, Doyle TJ, et al. (2000) Using remotely
632 sensed data to identify areas of risk for hantavirus pulmonary syndrome. Emerg Infect
633 Dis 63: 238-247.
- 634 5. Reisen WK, Meyer RP, Presser SB, Hardy JL (1993) Effect of temperature on the
635 transmission of Western equine encephalomyelitis and St. Louis encephalitis viruses
636 by *Culex tarsalis* (Diptera, Culicidae). J Med Entomol 30: 151-160.
- 637 6. Zhou G, Minakawa N, Githeko AK, Yan GY (2004) Association between climate
638 variability and malaria epidemics in the East African highlands. Proc Natl Acad Sci U
639 S A 101: 2375-2380.
- 640 7. Patz JA, Graczyk TK, Geller N, Vittor AY (2000) Effects of environmental change on
641 emerging parasitic diseases. Int J Parasitol 30: 1395-1405.
- 642 8. Anyamba A, Chretien J-P, Small J, Tucker CJ, Formenty PB, et al. (2009) Prediction
643 of a Rift Valley fever outbreak. Proc Natl Acad Sci U S A 106: 955-959.
- 644 9. Chretien J-P, Anyamba A, Bedno SA, Breiman RF, Sang R, et al. (2007) Drought-
645 associated chikungunya emergence along coastal East Africa. Am J Trop Med Hyg
646 76: 405-407.
- 647 10. Linthicum KJ, Anyamba A, Tucker CJ, Kelley PW, Myers MF, et al. (1999) Climate
648 and satellite indicators to forecast Rift Valley fever epidemics in Kenya. Science 285:
649 397-400.
- 650 11. Nicholls NA (1986) A method for predicting Murray Valley encephalitis in southeast
651 Australia using the Southern Oscillation. Aust J Exp Biol Med Sci 64: 587-594.
- 652 12. Bouma MJ, Dye C (1997) Cycles of malaria associated with *El Niño* in Venezuela. J
653 Am Med Assoc 278: 1772-1774.
- 654 13. Kovats R, Bouma MJ, Hajat S, Worrall E, Haines A (2003) *El Niño* and health.
655 Lancet 362: 1481-1489.
- 656 14. Engelthaler DM, Mosley DG, Cheek JE, Levy CE, Komatsu KK, et al. (1999)
657 Climatic and environmental patterns associated with Hantavirus pulmonary
658 syndrome, Four Corners region, United States. Emerg Infect Dis 5: 87-94.
- 659 15. Michaelsen J, Thompson LG (1992) A comparison of proxy records of *El Niño*
660 /Southern Oscillation. In: Diaz HF, Markgraf V editors. *El Niño: Historical and*
661 *Paleoclimatic Aspects of the Southern Oscillation*. New York: Cambridge University
662 Press. pp 323-348.
- 663 16. Yulaeva E, Wallace JM (1994) Signature of ENSO in global temperature and
664 precipitation fields derived from the microwave sounding unit. J Clim 7: 1719-1736.
- 665 17. Sobel AH, Held IM, Bretherton CS (2002) The ENSO signal in tropical Tropospheric
666 temperature. J Clim 15: 2702-2706.
- 667 18. Hastenrath S, Polzin D (2005) Mechanisms of climate anomalies in the equatorial
668 Indian Ocean. J Geophys Res 110, D08113, doi:10.1029/2004JD00498
- 669 19. Hastenrath S (2000) Zonal Circulations over the equatorial Indian Ocean. J Clim 13:
670 2746-2756.

- 671 20. Glantz MH (1991) Introduction. In: Glantz MH, Katz RW, Nicholls N, editors.
672 Teleconnections Linking Worldwide Climate Anomalies. New York: Cambridge
673 University Press. pp 1-12.
- 674 21. Ropelewski CF, Halpert MS (1987) Global and regional scale precipitation patterns
675 associated with the *El Niño/Southern Oscillation*. Mon Weather Rev 115: 1606-1626.
- 676 22. Gage KL, Burkot TR, Eisen RJ, Hayes EB (2008) Climate and vectorborne diseases.
677 Am J Prev Med 35: 436-450.
- 678 23. Anyamba A, Linthicum KJ, Small J, Britch SC, Pak E, et al. (2010) Prediction,
679 assessment of the Rift Valley fever activity in East and Southern Africa 2006–2008
680 and possible vector control strategies. Am J Trop Med Hyg 83(S2): 43-51.
- 681 24. Panning M, Grywna K, van Esbroeck M, Emmerich P, Drosten C (2008)
682 Chikungunya fever in travellers returning to Europe from the Indian Ocean region,
683 2006. Emerg Infect Dis 14: 416-422.
- 684 25. Linthicum KJ, Davies FG, Kairo A, Bailey CL (1985) Rift Valley fever virus (family
685 Bunyaviridae, genus *Phlebovirus*). Isolations from Diptera collected during an
686 interepizootic period in Kenya. J Hyg-Cambridge 95:197-209.
- 687 26. Hastenrath S, Polzin D, Mutai C (2007) Diagnosing the 2005 drought in equatorial
688 East Africa. J Clim 20: 4628-4637.
- 689 27. Hastenrath, S, Polzin D, Mutai C (2010) Diagnosing the droughts and floods in
690 equatorial East Africa during boreal autumn 2005-08. J Clim 23: 813-817.
- 691 28. Powers AM, Logue CH (2007) Changing patterns of chikungunya virus: re-
692 emergence of a zoonotic arbovirus. J Gen Virol 88: 2363-2377.
- 693 29. Lumsden WHR (1955) An epidemic of virus disease in southern province,
694 Tanganyika Territory, in 1952-53. II. General description and epidemiology. Trans
695 Roy Soc Trop Med Hyg 49: 33-57.
- 696 30. Jupp PG, McIntosh BM (1988) Chikungunya virus disease. In: Monath TP, editor.
697 The Arboviruses: Epidemiology and Ecology, Vol II. Boca Raton: CRC Press. pp
698 137-157.
- 699 31. Sang RC, Ahmed O, Faye O, Kelly CLH, Yahaya AA, et al. (2008) Entomologic
700 investigations of a chikungunya virus epidemic in the Union of the Comoros, 2005.
701 Am J Trop Med Hyg 78:77-82.
- 702 32. Mourya DT, Yadav P, Mishra AC (2004) Effect of temperature stress on immature
703 stages and susceptibility of *Aedes aegypti* mosquitoes to chikungunya virus. Am J
704 Trop Med Hyg 70: 346-350.
- 705 33. Vazeille M, Moutailler S, Coudrier D, Rousseaux C, Khun H, et al. (2007) Two
706 chikungunya isolates from the outbreak of La Réunion (Indian Ocean) exhibit
707 different patterns of infection in the mosquito, *Aedes albopictus*. PLoS One 2(11):
708 e1168. doi:10.1371/journal.pone.0001168
- 709 34. Tsetsarkin KA, Vanlandingham DL, McGee CE, Higgs S (2007) A single mutation in
710 chikungunya virus affects vector specificity and epidemic potential. PLoS Pathog
711 3(12): e201. doi:10.1371/journal.ppat.0030201
- 712 35. Turell MJ, Beaman JR, Tamariello RF (1992) Susceptibility of selected strains of
713 *Aedes aegypti* and *Aedes albopictus* (Diptera; Culicidae) to chikungunya virus. J Med
714 Entomol 29: 49-53.
- 715 36. de Lamballerie X, Leroy E, Charrel RN, Tsetsarkin K, Higgs S, et al. (2008)
716 Chikungunya virus adapts to tiger mosquito via evolutionary convergence: a sign of
717 things to come? Virol J 5: 33. doi: 10.1186/1743-422X-5-33
- 718 37. Hapuarachchi HC, Bandara KBAT, Sumanadasa SDM, Hapugoda MD, Lai YL, et al.
719 (2010). Re-emergence of chikungunya virus in South-east Asia: virological evidence
720 from Sri Lanka and Singapore. J Gen Virol 91: 1067-1076.

- 721 38. Ng LC, Hapuarachchi HC (2010) Tracing the path of chikungunya virus - evolution
722 and adaptation. *Infect Genet Evol* 10: 876-885.
- 723 39. Mackel R (1974) Dambos: A study in morphodynamic activity on the plateau regions
724 of Zambia. *Catena* 1: 327-365.
- 725 40. WHO (2007) Outbreaks of Rift Valley fever in Kenya, Somalia and United Republic
726 of Tanzania, December 2006-April 2007. *Weekly Epidemiological Record* 82: 169-
727 180.
- 728 41. Eisa M, Kheir El Sid ED, Shomein AM, Meegan JM (1980) An outbreak of Rift
729 Valley fever in the Sudan – 1976. *Trans Roy Soc Trop Med Hyg* 74: 417-419.
- 730 42. Saleh AS, Mohammed KA, Hassan MM, Bucci TJ, Meegan JM (1981) Antibodies to
731 Rift Valley fever virus in the human population of Sudan. *Trans Roy Soc Trop Med*
732 *Hyg* 75: 129-130.
- 733 43. NOAA/CPC ENSO Alert System: *El Niño* Advisory. Accessed April, 2010:
734 http://www.cpc.noaa.gov/products/analysis_monitoring/enso_advisory/
- 735 44. Paupy C, Ollomo B, Kamgang B, Moutailler S, Rousset D, et al. (2010) Comparative
736 role of *Aedes albopictus* and *Aedes aegypti* in the emergence of dengue and
737 chikungunya in Central Africa. *Vector-Borne Zoonotic Dis* 10: 259-266.
- 738 45. Trpis M (1972) Seasonal changes in the larval populations of *Aedes aegypti* in two
739 biotopes in Dar es Salaam, Tanzania. *Bull World Health Organ* 47: 245-255.
- 740 46. Andriamananjara SF, Randrianarivo-Solofonaina AE, Jeanmaire EM,
741 Ravololomanana L, Razafimanantsoa LT, et al. (2010) Rift Valley fever during rainy
742 seasons, Madagascar, 2008 and 2009. *Emerg Infect Dis* 16: 963-970.
- 743 47. Leroy EM, Nkoghe D, Ollomo B, Nze-Nkogue C, Becquart P, et al. (2009)
744 Concurrent chikungunya and dengue virus infections during simultaneous outbreaks,
745 Gabon, 2007. *Emerg Infect Dis* 15: 591-593.
- 746 48. Dyar HG (1928) The mosquitoes of the Americas. Washington: Carnegie Institute of
747 Washington. Publ. No. 387. 616 p.
- 748 49. Christophers SR (1960) *Aedes aegypti* L, the yellow fever mosquito. Its life history,
749 bionomics, and structure. New York: Cambridge University Press. 739 p.
- 750 50. Apandi Y, Nazni WA, Noor Azleen ZA, Vythilingham I, Noorazian MY, et al.
751 (2009). The first isolation of chikungunya virus from nonhuman primates in Malaysia.
752 *J Gen Mol Virol* 1: 35-39.
- 753 51. Burke DS, Nisalak A, Nimmannitya S (1985) Disappearance of chikungunya virus
754 from Bangkok. *Trans Roy Soc Trop Med Hyg* 79: 419-420.
- 755 52. Pavri K (1985) Disappearance of chikungunya virus from India and Southeast Asia.
756 *Trans Roy Soc Trop Med Hyg* 80: 491.
- 757 53. Kumarasamy V, Prathapa S, Zuridah H, Chem YK, Norizah I, et al. (2006) Re-
758 emergence of chikungunya virus in Malaysia. *Med J Malaysia* 61: 221-225.
- 759 54. Peters CJ, Linthicum KJ (1994) Rift Valley fever. In: Beran GB, editor. *Handbook of*
760 *Zoonoses*. Boca Raton: CRC Press, Inc. pp 125-138.
- 761 55. Centres for Disease Control and Prevention (2000) Outbreak of Rift Valley fever -
762 Saudi Arabia, August-October, 2000. *Morb Mortal Wkly Rep* 2000, 49: 905-908.
- 763 56. Anyamba A, Chretien J-P, Formenty PBH, Small J, Tucker CJ, et al. (2006) Rift
764 Valley fever potential, Arabian Peninsula [letter]. *Emerg Infect Dis* 12: 518-520.
- 765 57. Bicout DJ, Sabatier P (2004) Mapping Rift Valley fever vectors and prevalence
766 pattern using rainfall variations. *Vector-Borne Zoonotic Dis* 4: 33-42.
- 767 58. Linthicum KJ, Anyamba A, Britch SC, Chretien JP, Erickson RL, et al. (2007) A Rift
768 Valley fever risk surveillance system for Africa using remotely sensed data: potential
769 for use on other continents. *Veterinaria Italiana* 43: 663-674.

- 770 59. Little PD (2009) Hidden value on the hoof: Cross-border livestock trade in Eastern
771 Africa. Common Market for Eastern and Southern Africa Comprehensive African
772 Agriculture Development Program, Policy Brief Number 2, February 2009. Available
773 at: [http://www.nepad-caadp.net/pdf/COMESA CAADP Policy Brief 2 Cross Border Livestock Trade \(2\).pdf](http://www.nepad-caadp.net/pdf/COMESA CAADP Policy Brief 2 Cross Border Livestock Trade (2).pdf)
- 774
- 775
- 776
- 777

778

779 **Figure Legends**

780

781 **Figure 1. Summary correlation map between monthly NINO3.4 SST and rainfall**
782 **anomalies, 1979–2008.**

783

784 Correlation of sea surface temperatures and rainfall anomalies illustrate ENSO teleconnection
 785 patterns. There is a tendency for above (below) normal rainfall during *El Niño* (*La Niña*)
 786 events over East Africa (Southern Africa, Southeast Asia). Similar differential anomaly
 787 patterns were observed for other regions, especially within the global tropics. These extremes
 788 (above or below) in rainfall influence regional ecology and consequently dynamics of
 789 mosquito disease vector populations and patterns of mosquito-borne disease outbreaks.

790

791 **Figure 2. Outbreak locations of chikungunya (2004-2006) and Rift Valley fever (2006 –**
792 **2009).**

793

794 Symbols indicate distribution of recent outbreaks of chikungunya (2004-2006) shown by
 795 yellow dots and Rift Valley fever (2006-2009) shown by red , blue and green dots over
 796 eastern and southern Africa and the Indian Ocean islands.

797

798 **Figure 3. Cumulative rainfall anomalies over Eastern Africa, October-December, 2005.**

799

800 Negative rainfall anomalies correspond to the large-scale regional drought in Eastern Africa
 801 during October-December, 2005. Anomalies were calculated with reference to the 1995-2000
 802 long term mean. Epicenters of chikungunya outbreaks during this period are shown by the
 803 four open black dots.

804

805 **Figure 4. Cumulative rainfall anomalies and vegetation index anomalies for East Africa,**
806 **Sudan and Southern Africa.**

807

808 Patterns of rainfall anomalies preceding outbreaks of Rift Valley fever in (A) East Africa:
 809 September-December, 2006, (C) Sudan: June-September, 2007, and (E) Southern Africa:
 810 October, 2007- January, 2008. Each outbreak was preceded by persistent and above-normal
 811 rain on the order of +200 mm for a period of ~ 2-4 months (Fig. S2). This resulted in
 812 anomalous green-up of vegetation, creating ideal ecological conditions for the production of
 813 *Aedes* and *Culex* mosquito vectors that transmit Rift Valley fever virus to domestic animals
 814 and humans. Vegetation anomalies are shown for (B) East Africa: October, 2006-January
 815 2007, (D) Sudan: July-September, 2007, and (F) Southern Africa: October, 2007- January,
 816 2008. Rift Valley fever outbreaks are marked with yellow dots.

817

818 **Figure 5. Spatial and temporal anomaly patterns of NDVI, SST in relation to RVF**
819 **outbreaks.**

820

821 Spatial and temporal anomaly patterns in normalized difference vegetation index for selected
 822 areas of South Africa (A: 29°E and 32.5°E, averaged from 23°S to 27°S), Sudan (B: 32.5°E
 823 and 34°E, averaged from 11°N to 15°N), Tanzania (C: 34°E and 37°E, averaged from 4.5°S to
 824 8.5°S) and Kenya (D: 37°E and 42.5°E, averaged from 2°S to 2°N). Regions were plotted by
 825 geographic position west to east and represent areas with dense concentrations of Rift Valley
 826 fever cases. NDVI anomalies are depicted as percent departures from the 2002-2008 long-
 827 term mean, and show the response of vegetation to variations in rainfall. Periods shaded in

828 green to purple indicate above-normal vegetation conditions associated with above-normal
 829 rainfall. Periods of persistent drought or below normal rainfall are shown in shades of yellow
 830 to red. Each Rift Valley fever outbreak was preceded by above-normal vegetation conditions
 831 resulting from persistent above-normal rainfall in the Horn of Africa and Sudan in 2006-
 832 2007. Chikungunya epidemics occurred over East Africa and Indian Ocean islands during the
 833 2005-2006 drought period shown by negative NDVI anomalies from 2005-2006 [D: red
 834 boxed area]. Clusters of epidemics/epizootics of Rift Valley fever in East Africa (2006-2007)
 835 and Sudan (2007) occurred during the *El Niño* event of 2006-2007 when there were
 836 concurrent anomalously warmer WIO and Nino 3.4 SSTs. The transition to *La Niña*
 837 conditions in late 2007-early 2008 spatially shifted the area of above-normal rainfall and
 838 enhanced vegetation conditions to South Africa and Madagascar between February-March,
 839 2008 and sporadically between February-March, 2009 in South Africa, leading to outbreaks
 840 of Rift Valley fever in these regions. This illustrates that spatial displacements in extreme
 841 rainfall and ecological conditions driven by large-scale climate mechanisms such as ENSO
 842 and regional circulation lead to spatial-temporal shifts in areas at risk for outbreaks of these
 843 mosquito-borne diseases.

844

845 **Figure 6. Frequency distributions of chikungunya outbreak events in relation to**
 846 **temperature.**

847 Frequency distributions of chikungunya outbreak events and 4-month cumulative temperature
 848 anomalies for East Africa (A), Central Africa (B), South Asia (C), and Southeast Asia (D).
 849 The 4-month anomaly threshold was used to represent periods of either cool temperatures or
 850 drought and extreme high temperatures. The dashed line at zero depicts the 1979-2009 long-
 851 term mean temperature, with warmer-than-normal temperatures shown to the right (red) and
 852 cooler-than-normal temperatures shown to the left (blue) of the line. Cases shown to the right
 853 of the dashed line occurred during periods of elevated temperature with a persistence of 4
 854 months.

855

856

857 **Figure 7. Frequency distributions of chikungunya outbreak events in relation to**
 858 **precipitation.**

859 Frequency distributions of chikungunya outbreak events and 4-month cumulative
 860 precipitation anomalies for East Africa (A), Central Africa (B), South Asia (C), and Southeast
 861 Asia (D). The 4-month anomaly threshold was used to represent periods of either persistent
 862 above-normal rainfall/wetness or persistent drought conditions. The dashed line at zero
 863 depicts the (1979-2009) long term rainfall, with greater-than-normal precipitation shown to
 864 the right (blue) and lower-than-normal precipitation shown to the left (red) of the line. Cases
 865 shown to the left of the dashed line occurred during periods of drought with a persistence of 4
 866 months.

867

869 **Table Legends**
870871 **Table 1. Climate and disease data sets used in the study.**
872

873 All anomaly indices were computed as monthly departures from their respective
 874 climatological values (long-term means) defined by the periods shown above. NINO 3.4 SST
 875 index was computed by the National Oceanic and Atmospheric Administration Climate
 876 Prediction Center (NOAA/CPC) as part of operational ENSO monitoring activities. We
 877 computed the WIO index directly from the global SST data based on previous research by
 878 Linthicum et al. (1999). SPOT Vegetation data were processed by Vlaamse Instelling voor
 879 Technologisch Onderzoek (VITO) in Belgium into 10-day composite data. Monthly
 880 composites, long-term means, and anomalies from these data were processed by the
 881 NASA/Global Inventory Modeling and Mapping Studies (GIMMS) group.
 882

Data	Source	Coverage	Climatolog y period	Purpose
NINO 3.4 SST	NOAA/CPC	5°N–5°S, 170°W– 120°W, monthly	1971-2000	teleconnections
WIO	NOAA/CPC	10°N-10°S, 40°-64°E, monthly	1971-2000	teleconnections
GPCP Rainfall	NOAA/CPC	global, monthly, 1°	1979-2009	teleconnections, chikungunya
NCEP Air Temperature	NOAA/CPC	global, monthly, 2.5°	1968-1996	chikungunya
ARC Rainfall	NOAA/CPC	Africa, monthly, 10 km spatial resolution	1995-2006	Rift Valley fever, chikungunya
SPOT Vegetation AVHRR NDVI	VITO NASA/GIMM S	Africa, monthly, 1 km, 8 km spatial resolution	May 1998- April 2008	Rift Valley fever
Disease Data (Rift Valley fever,	CDC-K, WHO, FAO, OIE and	episodic (Rift Valley fever: 2006-2009,	N/A	climate-ecology-disease teleconnections and

chikungunya)	various national governments	chikungunya: 1952- 2010)		relationships
--------------	------------------------------------	-----------------------------	--	---------------

883

884

Table 2. Results of logistic regression of Rift Valley fever presence/absence on cumulative rainfall anomalies

887

888 Logistic regression of Rift Valley fever presence/absence on cumulative rainfall anomalies
 889 over a 4 month period. For each region, the top row presents results for the intercept term (β_0)
 890 and the bottom row (β_1) for the rainfall anomaly term. Regional Rift Valley fever outbreaks
 891 were significantly positively correlated with persistently above-normal cumulative rainfall
 892 over a 4 month period (99.9% confidence, $\beta_1 > 0$), except in Madagascar ($\beta_1 < 0$).
 893

Region		coefficients	std error	z value	p(> z)	confidence
East Africa (n=383)	β_0	-3.1202	0.3050	-10.231	$< 2 \times 10^{-16}$	> 99.9%
	β_1	2.8096	0.3264	8.608	$< 2 \times 10^{-16}$	> 99.9%
Sudan (n=257)	β_0	-4.6153	0.8952	-5.156	2.53×10^{-7}	> 99.9%
	β_1	26.5603	5.1397	5.168	2.53×10^{-7}	> 99.9%
South Africa (n=185)	β_0	-2.022	0.260	-7.777	7.40×10^{-15}	> 99.9%
	β_1	4.575	1.106	4.135	3.55×10^{-5}	> 99.9%
Madagascar (n=65)	β_0	-2.0897	0.5849	-3.573	0.000353	> 99.9%
	β_1	-10.6091	3.8901	-2.727	0.006387	99.9%

894

895

896

897

898 **Supporting Figure Legends**
899900 **Figure S1. SST anomalies during the peak of the *El Niño* event from December, 2006-**
901 **February, 2007.**902
903 Global seasonal equatorial sea surface temperature anomalies during the peak of the *El Niño*
904 event December, 2006-January, 2007.905
906 **Figure S2. SST anomalies during the peak of the *La Niña* event from December, 2007–**
907 **February, 2008.**908
909 Global seasonal equatorial sea surface temperature anomalies during the peak of the *La Niña*
910 event December, 2007-February, 2008.911
912 **Figure S3. Cumulative daily rainfall profiles for periods of Rift Valley fever activity for**
913 **selected outbreak sites.**914
915 Cumulative daily rainfall (green lines) profiles for periods of Rift Valley fever activity and
916 mean long-term cumulative daily rainfall (red lines) for sites with reported Rift Valley fever
917 activity. Dotted line represents when the first case of Rift Valley fever was identified at each
918 location. Each of the outbreak locations was preceded by above-normal rainfall for 3-4
919 months.920
921 **Figure S4. Distribution of 2004-2010 chikungunya outbreaks in relation to human**
922 **population density.**923
924 Each symbol represents the year(s) when an outbreak was reported at a specific geographic
925 location. Most chikungunya activity has occurred in locations with high population densities
926 (>500 people per square kilometre).927
928

929

Figure 1

[Click here to download high resolution image](#)

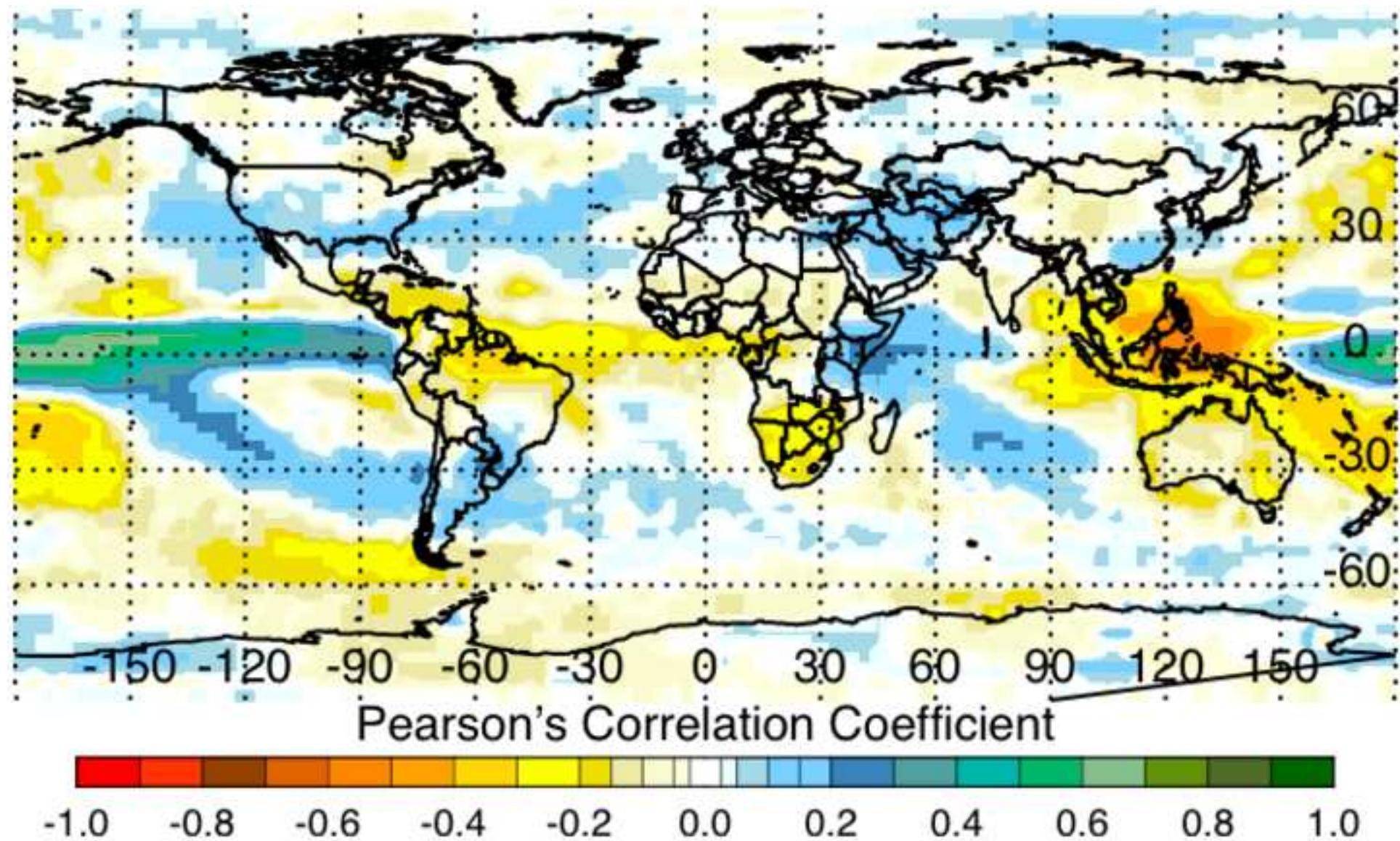


Figure 2

[Click here to download high resolution image](#)

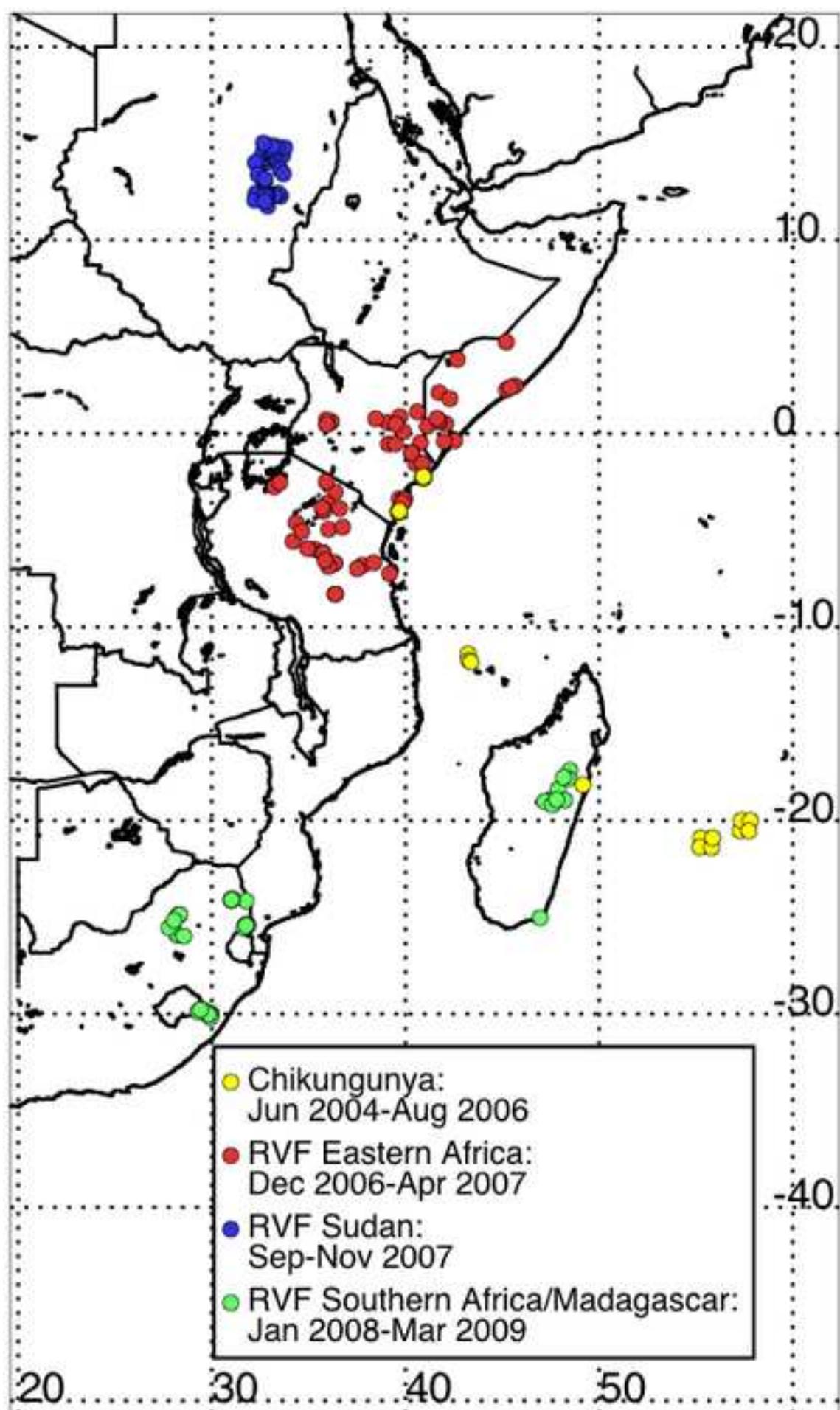


Figure 3

[Click here to download high resolution image](#)

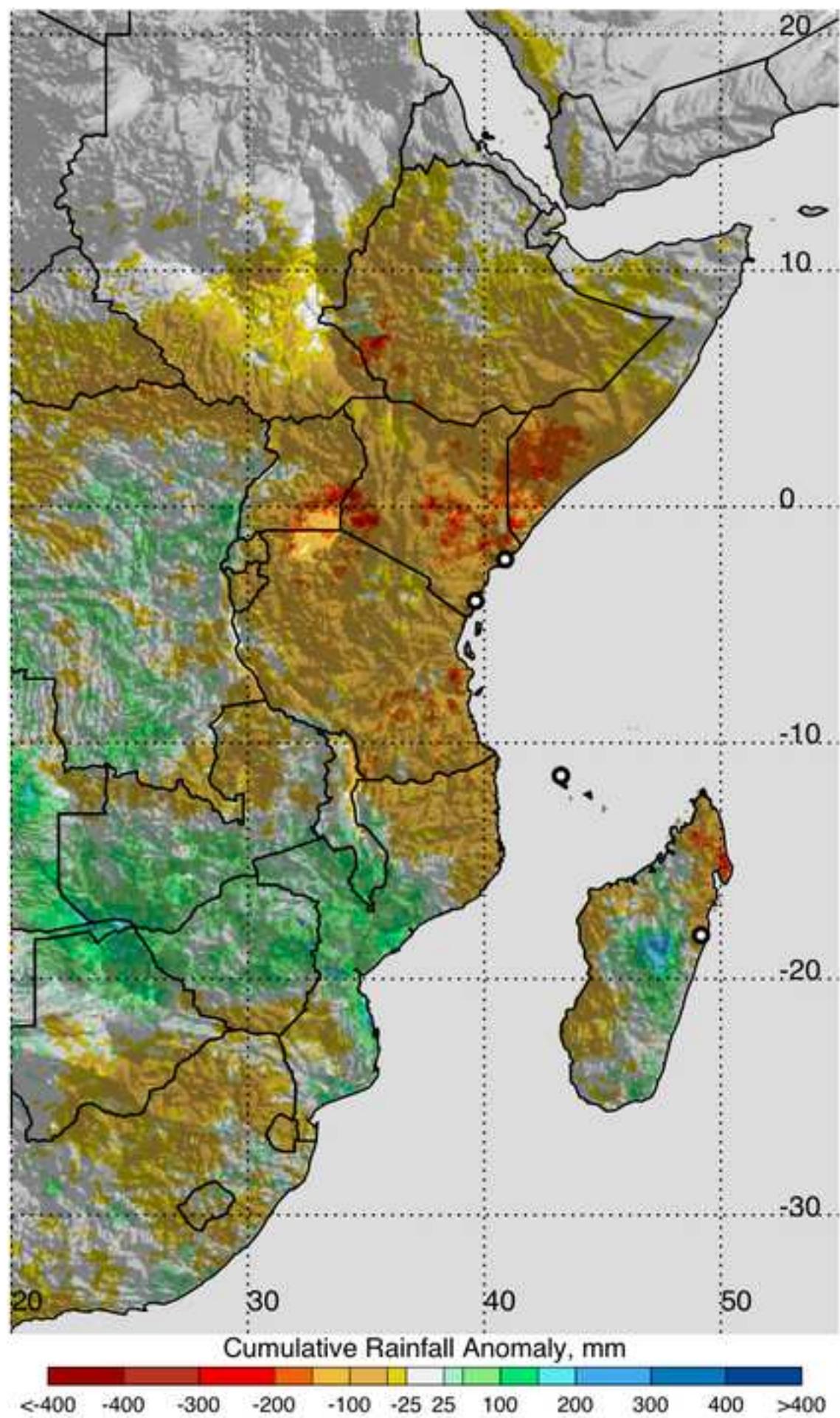


Figure 4

[Click here to download high resolution image](#)

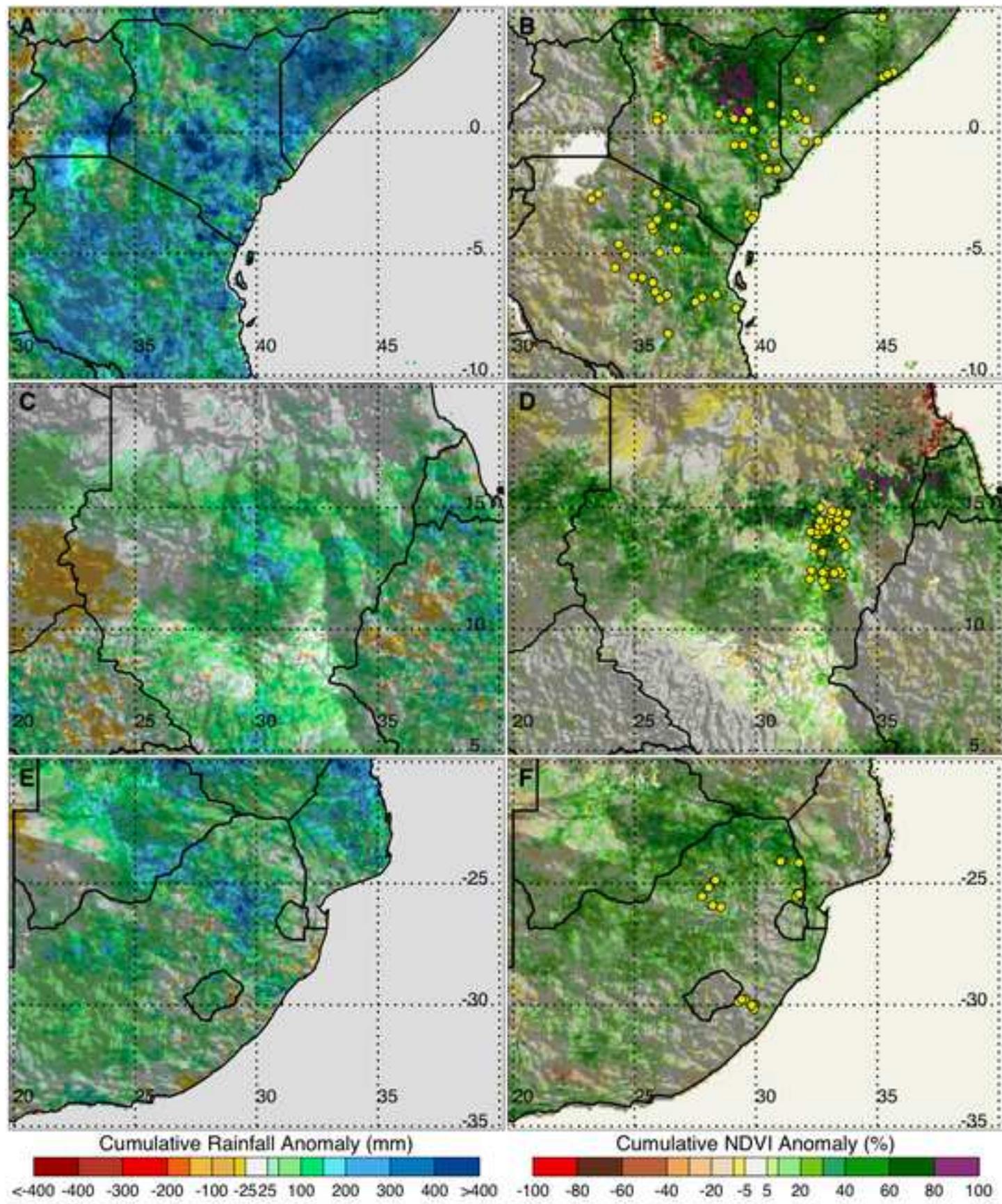


Figure 5

[Click here to download high resolution image](#)

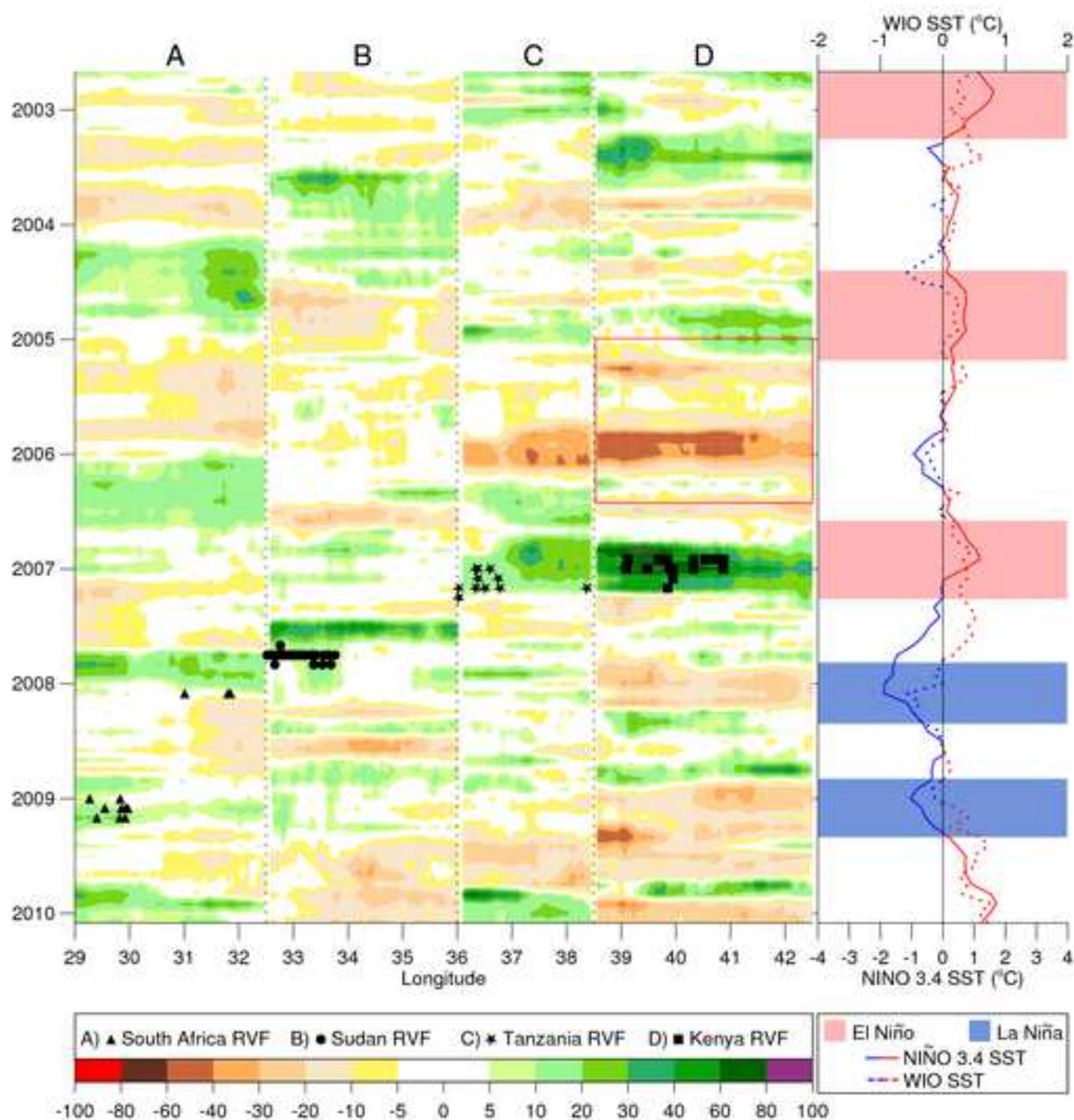


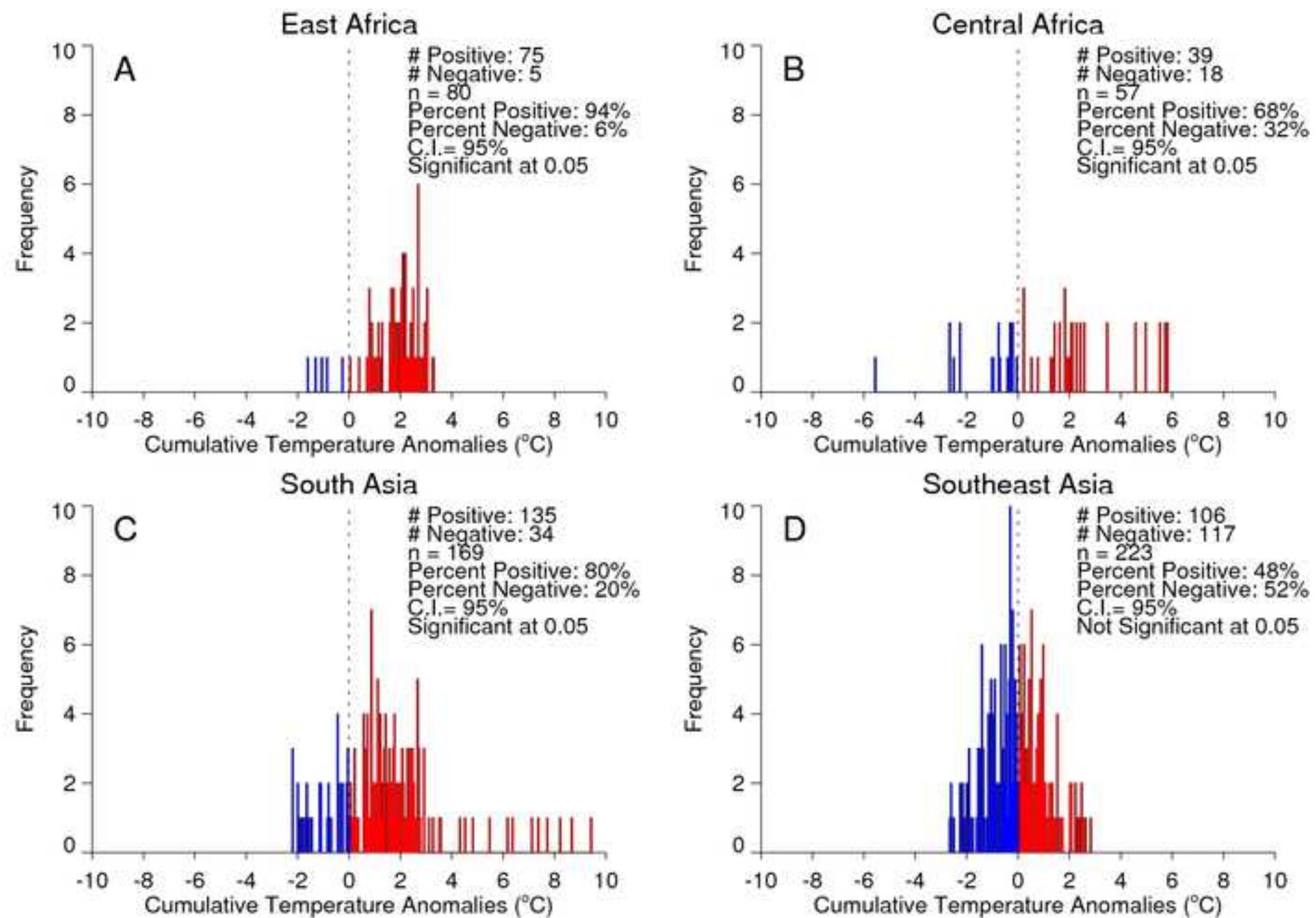
Figure 6[Click here to download high resolution image](#)

Figure 7

[Click here to download high resolution image](#)

